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VSOP and stellar sources - the case of LS I $+61°303$

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Abstract. Space-VLBI observations of stellar sources represent a challenge since there are few sources with sufficiently high brightness temperature for detection on space-ground baselines. X-ray binaries (XRB) are among the few types of stellar radio sources that can be detected. Observations of the unusual X-ray and γ-ray binary system LS I $+61°$ 303 obtained with the HALCA satellite and a 20-element ground array are described. The data in this 48-hour experiment represent some of the best quality VLBI observations of LS I $+61°$ 303. No fringes were detected on HALCA baselines. 10-minute snapshot images were produced from the global ground array data and reveal an expansion velocity of 800 km s^{-1}. Some of these image data reveal hints of more extended emission but high-SNR closure phase data do not support relativistic outflow in the plane-of-the-sky in LS I $+61°$ 303. The largest closure phase rates are consistent with an outflow of ~ 1000 km s^{-1} as deduced from the image data. The closure phases also show no evidence of structure variation on size scales greater than ~ 10 mas. A number of issues related to VSOP2 observations of stellar radio sources are raised.

1. Introduction

A challenge of observational astrophysics with radio interferometers is the fundamental limitation the observing array places on brightness temperature sensitivity. The sensitivity of the individual telescope elements in the array determines the flux density limit. The HALCA spacecraft had a 7σ sensitivity in a few minutes to a ground-based telescope of ~ 100 mJy, and so for an array with $B_{\max} \sim 10,000$ km (a resolution of ~ 1 mas at 5 GHz) this implies a brightness temperature limit of $T_B \sim 10^{10}$ K. Consequently the types of stellar sources that could be detected on baselines to HALCA was limited to masers, pulsars, and some XRBs. There are undoubtedly others types of sources that could be detected, but they will exhibit either outburst phenomena or coherent emission processes.

The subjects of maser and pulsar observations are well covered by other papers presented at the meeting and the previous VSOP symposium. In this paper, the specific case of VSOP observations of the high mass XRB LS I $+61°$ 303 will be described. Special attention will be given to some properties of the radio emission in LS I $+61°$ 303 as a means to reveal some of the challenges that need to be addressed for future space-VLBI observations of stellar sources.

2. What is LS I $+61^\circ 303$?

The luminous early-type star LS I $+61^\circ$ 303 was discovered as a radio source by Gregory & Taylor (1978), who proposed an association with the COS-B γ-ray source 2CG 135+01 (Hermsen et al. 1977). The radio emission was shown to have regular, non-thermal outbursts with a period of 26.51 days (Taylor & Gregory 1984); the flux density rises from a quiescent level of around 20 mJy to a peak of up to 300 mJy over $\sim$ 2 days, and then decays over $\sim$ 8 days to its quiescent level. The period is related to the highly eccentric orbit of a compact object around a rapidly rotating B0e star (Hutchings & Crampton 1981; Grundstrom et al. 2007). The 26.5-day periodic behavior is also manifest at other wavelength regions: IR (Paredes et al. 1994), X-ray (Paredes et al. 1997) and, most recently γ-ray energies (Albert et al. 2006; Maier 2007).

Variable TeV emission has been detected in three other high-mass XRB systems. Together they form a group of objects that have been referred to as Binary TeV sources (BTVs). PSR B1259-63 is a 3.4-yr period massive binary system with a pulsar in an eccentric orbit around a B0e star (Johnston et al. 1992). The TeV and X-ray emission is interpreted as inverse-Compton (IC) emission due to relativistic electrons accelerated in a wind-collision between the pulsar wind and that of the massive companion (e.g. Tavani & Arons 1997). Cygnus X-1 is a well-established micro-quasar system with clearly observed relativistic jets (e.g. Stirling et al. 2001; Fender et al. 2006). The situation in both LS 5039 and LS I $+61^\circ$ 303 is far from clear. In LS5039, there is evidence of relativistic jets but the picture is not completely clear (Ribo et al. 2008). In LS I $+61^\circ$ 303, both micro-quasar (e.g. Massi et al. 2004) and pulsar-wind nebulae (Dhawan et al. 2006) models have been advanced, with the merits of each scenario discussed by Romero et al. (2007, and references therein). The remainder of this paper will discuss the insights revealed by VSOP observations of LS I $+61^\circ$ 303 and how they may inform this discussion.

3. Previous VLBI observations

VLBI observations of LS I $+61^\circ$ 303 have been completed by a number of different groups. Observations with the EVN near peak flux indicate a low expansion velocity of $\sim$ 600 km s^{-1} (Taylor et al. 1992). However, an expansion velocity of $\sim 18,000$ km s^{-1} was measured during a mini-outburst observed during the main outburst (Peracaula et al. 1998). More recently, evidence for relativistic expansion has been presented from EVN and MERLIN observations. Massi et al. (2001) observed an extension of the central source to the SE. The lack of a corresponding symmetric feature to the NW led to an interpretation of a Doppler amplified outflow close to the line-of-sight with an inferred ejection speed of 0.4c. A more recent MERLIN observation suggests a similar structure, though with a double-sided jet that extends up to 200 AU ($\sim$ 70 mas) from the central source and which precesses significantly in 24 hours (Massi et al. 2004). This is interpreted as due to a jet with an outflow speed of 0.6c. Clearly, these observations do not present a consistent picture of the dynamical evolution of the radio emission arising in LS I $+61^\circ$ 303.

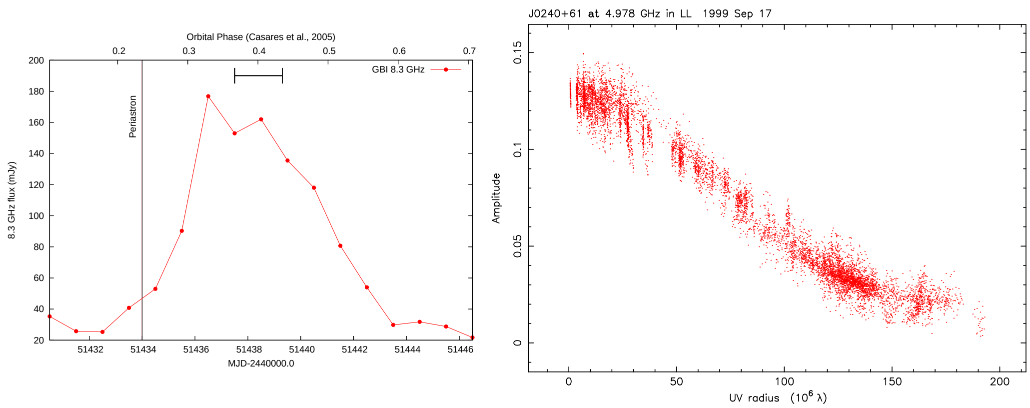

Figure 1. Left: The epoch of VSOP observations (horizontal bar) relative to an outburst in LS I +61° 303 as observed by the GBI. The orbital phase from Casares et al. (2005) is shown, and the phase of periastron. Right: Visibility distribution of LS I +61° 303 over 1 hour. The source is clearly resolved.

4. VSOP observations of LS I +61°303

Observations over 48 hours were obtained on 1999 September 17 at 5 GHz with HALCA and a 20-element ground array including some of the largest telescopes available (the phased-VLA, Effelsberg, Jodrell Bank). The goal was to image LS I +61° 303 with sub-milliarcsecond resoltion to observe structural changes as the source evolved during the 2 days of outburst. Though VSOP observations pre-date some of the observations described in Sec. 3., they represent perhaps the largest global array assembled to observe LS I +61° 303, and such high-SNR data is arguably the best available today for this source. They have been described previously by Taylor et al. (2000), but more recent analysis is included here.

Unfortunately, the observations started approximately 60 hours after the onset of outburst (Fig 1 - left), and data was collected during decline. Furthermore, fringes on baselines to the HALCA spacecraft were not detected. The visibility distribution from part of the observation is shown in Fig 1 (Right). This plots demonstrates that at the spatial frequencies sampled by HALCA baselines (> 200Mλ), the correlated flux (~ 20 mJy or less) is too low for direct fringe detection (see comments in Sec. 5.).

The ground-telescope array data alone provides a very high-quality VLBI observation of LS I +61° 303 during the decline phase of an outburst. Standard phase-referencing techniques were used in the ground observations, enabling antenna gain calibration using the bright quasar J0228+67 at a few degrees distance every 20 minutes. Snapshot images every 10 minute were generated, with two examples from 112 total images shown in Fig. 2.

The image data show the source has a maximum extent of ~ 4 mas, similar to previous observations taken during quiescence. Comparison of visibility data on each of the two days shows evidence for a ~ 0.3 mas angular expansion over 24 hours, corresponding to an expansion of 0.6 AU at a distance of 2 kpc (Frail & Hjellming 1991), and an inferred expansion velocity of ~ 800 km s^{-1}.

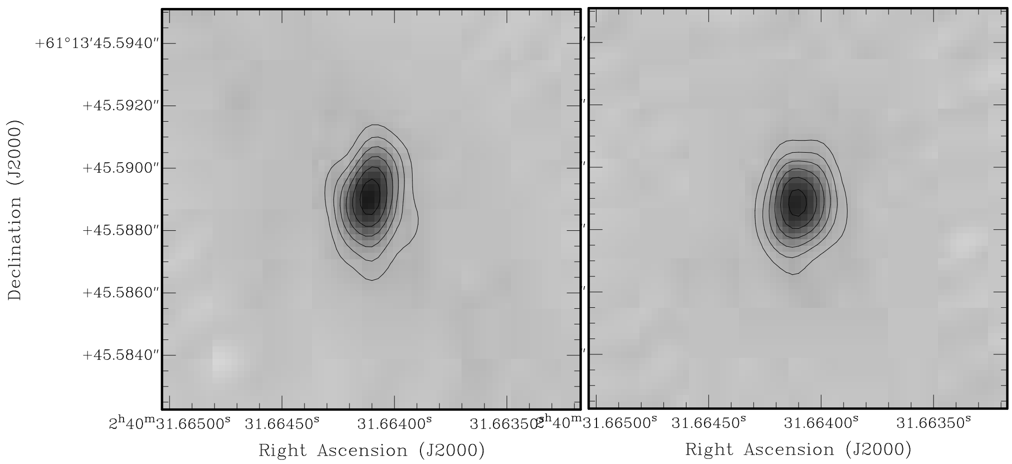

Figure 2. Two 10-minute images from the 113 in the observation. Contours are $8, 12, 18 \ldots 80\%$ of peak. Frame 21 (left) and Frame 79 (right) are typical examples. Visibility modelling of data from each day reveals expansion of ~ 0.3 mas over 24 hours.

A feature seen in some of these images is low surface brightness extensions to the central emission region. These extensions are roughly symmetric about the central source and have been interpreted as emission from high-velocity outburst ejecta. If they are associated with the outburst the inferred expansion velocity is $42,000$km s^{-1}, and broadly consistent with expansion deduced from MERLIN and EVN observations by Massi et al.

However, interpretation of the extensions in some of the images is hindered by a) the inability to follow the features from one 10-minute snapshot to the next and b) the symmetric nature of the features. This led us to consider if these were artefacts of calibration errors. A robust technique for eliminating calibration artefacts is to examine closure quantities, particularly phase where any time variation in closure phase is due *only* to intrinsic properties of the radio source. This is particularly useful with high-SNR data since even small closure phase variations can be readily detected.

Closure phase for a number of antenna triangles is shown in Fig. 3 and several things can be deduced readily. Firstly, on 10-mas size scales represented by the EB-JB-MC triangle (bottom frame), the closure phase is identically zero. This implies LS I $+61^\circ\,303$ is a point source on these angular scales with no variable structure during this observation. The next important feature is that the largest changes in closure phase are $\sim 20^\circ$ over a few hours. What does this imply? 20° is approximately 1/20 of the beam so for a 1 mas beam this corresponds to an asymmetric structure changes of $\sim 50\mu$as. Over a few hours, this corresponds to an expansion of ~ 1000km s^{-1}, consistent with the visibility modelling analysis. Most importantly, at 2 kpc an expansion in the plane-of-the-sky at $1c$ would result in a closure phase rate of 180° in 8 minutes, which would be easily seen, especially in such high-SNR data. Though the phase rate is dependent on the degree of asymmetry of the structure change, there

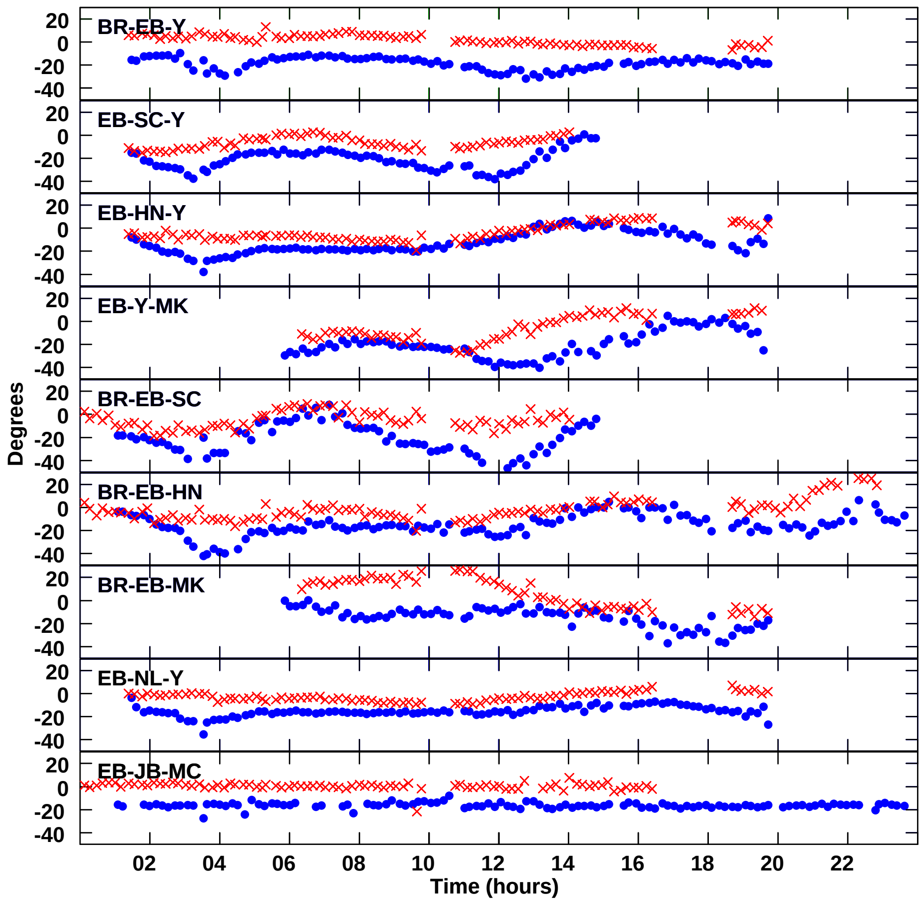

Figure 3. Closure phase every 10 minutes from September 16 (dots) and 17 (crosses) (Vivek Dhawan, priv. comm.) The closure phase from each day is offset by 20° for clarity . A number of different three antenna groups are shown, all with very high SNR data.

is no evidence of relativistic expansion in the closure phase. This leads to the conclusion that the extensions are an artefact of calibration error.

5. VSOP2 and stellar radio astrophysics

Stellar observations with VSOP were particularly challenging due to the lack of the necessary sensitivity on HALCA to directly detect fringes. However, the observations of LS I +61° 303 provide some useful insight for planning stellar radio observations with future space-VLBI missions such as VSOP2.

It is important that sensitivity is maximized. This implies the use of the most sensitive ground-based telescopes, not only in terms of collecting area (e.g. phased-VLA, Effelsberg, GBT etc), but also the observing frequency. This suggests 8.6 GHz will be the most suitable frequency since it offers an ideal combination of sensitivity on the ground and, for non-thermal sources, a higher flux

than at the higher frequency observing bands specified for VSOP2. Ideally, the most sensitive 8.6-GHz system possible should be available on the spacecraft.

An imperative for stellar observations in future missions is a source switching or "phase-referencing" capability with the spacecraft. This ability was not available with HALCA. First, it is important to be able to involve the spacecraft in fringe-finding observations in order to establish the clock and orbit geometry offsets. If a source is sufficiently bright, phase-referencing observations can be done to utilise self-calibration to solve for time evolution of these parameters and the gain phase of the spacecraft. Further more, this provides an ability to improve orbit definition through astrometry.

The VSOP observations of LS I $+61^{\circ}\,303$ were planned for a predicted time of outburst. Unfortunately, the onset of outburst was missed by 60 hours. Observations during outburst could only have been assured through a dynamic scheduling capability. Certainly if transient science is a key project for VSOP2 then a dynamic scheduling capability that permits spacecraft command upload on short timescales is a necessity.

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